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Preface

Wireless Body Area Networks (WBANs) are expected to promote new applications for the ambulatory health monitoring of chronic patients and the elderly population, aiming to improve their quality of life and independence. These networks are composed by wireless sensor nodes that measure physiological variables and transmit it, for example, to the patients' smartphone, which may acts as a gateway to a remote medical assistance service. A key element of such sensor nodes is the wireless transceiver as it often dominates the overall power budget. Therefore, to provide a high degree of energy autonomy, wireless transceivers with an ultra low power consumption are needed. In this book, a transceiver architecture and implementation is presented, which targets such highly power constrained applications and employs the Bluetooth low energy standard.

At the architectural level, four main strategies are identified to obtain an ultra low power consumption. First, a direct-conversion receiver architecture is selected as it relaxes the requirements for the local oscillator and allows for a low power baseband section. Secondly, the number of active radio-frequency (RF) blocks has to be minimized in order to end up with as few RF nodes as possible that have to be driven by power-hungry circuits. Third, the remaining RF nodes have to be implemented with a high impedance level, which leads to a low required transconductance in the driving blocks and so reduces the power consumption. Finally, a low complexity demodulation scheme avoiding quadrature multi-bit analog-to-digital converters (ADCs) is needed.

The resulting transceiver architecture employs a passive receiver frontend architecture and a transformer at the antenna interface to boost the internal RF impedance. The carrier frequency is generated by a quadrature voltage controlled oscillator (QVCO), which is directly modulated to also synthesize the required signaling for transmission. In the baseband, the proposed transceiver employs a phase-domain ADC (Ph-ADC) which needs only 4 bits of resolution to demodulate the received signal.

In order to further improve the energy autonomy of the wireless sensor node, the possibilities for including an RF energy harvester with the presented transceiver frontend are studied. A fundamental problem that has to be resolved is the decoupling of the harvester from the transceiver while using the same antenna. In the proposed architecture the harvester is decoupled with an RF-switch that can be turned on passively, i.e., by utilizing the incoming RF power only. This approach stands out due to its low degradation of the transceiver performance as well as its small area occupation and hence low implementation cost.

On circuit level, the main contributions of this book are (a) a passive cancelation network to reduce the magnetic coupling-induced quadrature error of the QVCO, (b) a simple 4-transistor cell to directly modulate the QVCO tank capacitance in aFsteps, which has been verified to be sufficiently stable within the industrial temperature range, (c) a new current-domain linear combiner to provide the phase generated signals for the 4-bit Ph-ADC, which allows for a both area- and power-efficient implementation, and (d) an RF-switch that can be turned on without an external power supply using a start-up rectifier.

The proposed transceiver is implemented in a 130 nm CMOS technology using four integration steps which progressively complete the transceiver with the harvester. In the receive mode, the measured power consumption of 1.1 mW advances the state of the art as it is the lowest reported for a narrowband transceiver in the 2.4 GHz ISM band, which fulfills one of the typical WBAN standards. With a sensitivity of −81.4 dBm the receiver also achieves a competitive performance providing a sufficient link budget for a short-range data link. Concerning the performance in transmit mode, the power consumption of 5.9 mW and 2.9 mW in normal and back-off mode, respectively, is among the lowest reported so far for narrowband transmitters. However, the total transmitter efficiency of up to 24.5 % is significantly higher compared to other implementations due to the increased internal RF impedance. The harvester achieves a decent peak efficiency of 15.9 % and is able to progressively charge up an energy storage device for pulsed input signals emitted by an active WLAN router, for an expected distance of up to approximately 30 cm. Measurements also verify that the degradation of the transceiver, which arises from sharing the same antenna interface with the harvester, is less than 0.5 dB.

In conclusion, an ultra low power transceiver architecture for WBAN applications is presented which advances the state of the art in various aspects, as verified experimentally. Also the compatibility of the proposed architecture with energy harvesting techniques is shown, providing a possibility to improve the energy autonomy of wireless sensor nodes.

This book is organized as follows. After an introductory Chap. 1, Chap. 2 reviews the state-of-the-art of wireless low power transceivers. Then, Chap. 3 presents the four main strategies to reduce the power consumption and Chap. 4 describes the proposed transceiver in detail. Chapter 5 shows the co-integration of the energy harvester and finally Chap. 6 concludes this thesis.

Sevilla, July 2012

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Chapter 1
Introduction

The technological progress in wireless communication has greatly changed our habits in the past decades, mainly perceived today by the prominent role that smartphones play in our life. Especially, the miniaturization and cost reduction due to modern submicron CMOS processes has allowed to integrate a variety of services in such handheld devices. Following this trend, we can anticipate that smaller and smaller devices will be equipped with wireless interfaces in the future. Currently, peripheral wireless devices usually employ short-range communication protocols such as Bluetooth or ZigBee to form a wireless body area network (WBAN). However, since small devices are often highly constrainted with respect to the available power supply, the Bluetooth consortium has adopted in 2009 an extension to the standard, namely bluetooth low energy [3]. This new protocol is expected to greatly reduce the power consumption of the wireless interface and so promote many new applications.

Especially in the field of ambulatory health monitoring, WBANs have the potential to substantially improve the quality of life and independence of chronic patients and elderly people [116]. These networks are composed by wireless sensor or actuator nodes used for measuring physiological variables (e.g., glucose level in blood or body temperature [10]) or controlling therapeutic devices (e.g., implanted insulin pumps [86]). WBANs typically use a conventional star topology in which nodes acquire, process and transmit information to the central hub, that would be included in a smartphone for a typical ambulatory health monitoring application, as illustrated in Fig. 1.1. In this scenario, the smartphone can also serve as a real-time gateway to a medical control point or a remote assistance service by employing a long-range communication protocol [10, 86].

Wireless sensor nodes should exhibit a high degree of energy autonomy, which leads to the need for low-power consumption solutions in order to extend the battery lifetime or even make the node supply to rely on energy harvesting techniques. Typically, the power budget of the sensor node is dominated by the wireless link [48], and hence many efforts have been directed during the last years toward the implementation of power efficient transceivers (TRXs) [9, 14, 15, 18, 24, 26, 34, 36, 37, 41, 42, 45, 50, 57, 60, 62, 64, 67, 91, 101, 104, 109, 119, 120, 123, 133, 139,

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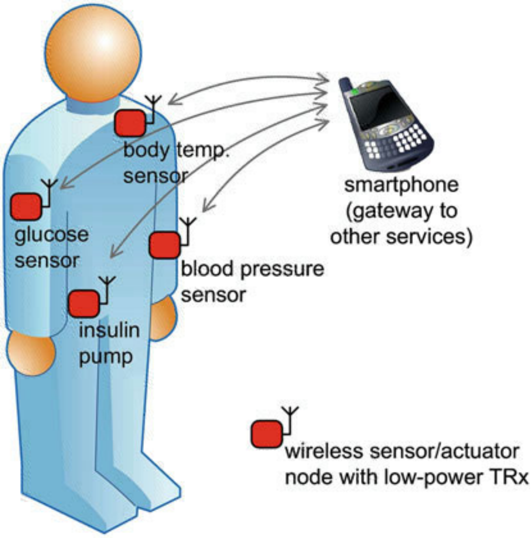

Fig. 1.1 Wireless body area network (WBAN)

140, 141, 147, 149, 151]. However, especially the most power efficient TRXs usually employ proprietary wireless interfaces which are often spectrally inefficient [14, 15, 18, 41, 45, 50, 91, 101, 120, 133, 139, 140, 149, 151]. Unlike to these solutions, the objective of this work is to reduce the power consumption while using a standardized and widely available wireless interface, namely bluetooth low energy (BLE). Sensor nodes that can easily connect to a smartphone without the need of proprietary read-out devices provide a second dimension of autonomy for the patient, apart from the battery lifetime. Additionally, the link layer of BLE supports AES encryption and key exchange algorithms to protect the highly sensitive personal data from unauthorized access. Finally, the 2.4 GHz industrial, scientific, and medical (ISM) band, in which BLE operates, is available worldwide and it allows for compact antennas designs, not larger than a few centimeters [2].

The methodology to reduce the power consumption employed in this book is rather an optimization at the architectural level than at the block level. For example, instead of optimizing a low-noise amplifier (LNA) for ultra low-power consumption, the necessity of an LNA at all is questioned. Considering the link budget needed for WBAN applications, an LNA is not necessarily required and a completely passive receiver (RX) frontend is sufficient. Similarly, questioning the necessity of an up-conversion mixer in the transmitter (TX) leads to the conclusion that the required signaling can be generated without a mixer by directly modulating the local oscillator (LO). Of course, optimization at the architectural level alone becomes worthless unless it is followed by a very power-aware design of the blocks.

The proposed transceiver has been implemented in standard CMOS technologies in order to allow for a low-cost solution, which is an important factor for wireless sensor nodes. At the beginning of this project, the feasibility of the quadrature LO was verified with two test chips (chip 1a and 1b) in a 90 nm 1P7M[1] CMOS technology. For availability reasons, the following implementations of the transceiver (chips 2–4) have been realized in a 130 nm 1P6M CMOS technology. Both technologies were provided by STMicroelectronics. The transceiver was implemented in two integration steps. In chip 2, the complete frequency synthesizer including PLL and direct modulation was integrated. To provide the realistic loading of the LO and to test the passive RX concept, also a provisional transceiver frontend was implemented in this run. In chip 3, the frontend was refined and a phase-domain demodulator was added to the RX baseband, completing the transceiver. In the final integration step (chip 4), an RF-to-DC converter was added to the frontend in order to show that the selected topology is also suitable for co-integration of RF energy harvesting without significant degradation.

1.1 Project Objectives and Organization

The main objective of this book is the implementation of a BLE transceiver in a low-cost CMOS technology with an ultra low-power consumption. Obviously, the BLE standard as well as the targeted application impose a set of specifications which have to be fulfilled, especially the blocking requirements with respect to near-by interferers. Complying with these requirements is particularly important considering that the transceiver operates in the 2.4 GHz ISM band, which is used by many applications. To provide a concise and handy overview, the specifications for the BLE signaling and the blocking requirements are summarized in the Appendix A.

A key requirement given by the application is the expected communication range. Taking into account channel imperfections, a certain link budget must be provided by the transceiver. Defining the link budget as the ratio of transmitter output power to receiver sensitivity ($P_{\text{out}}/P_{\text{sens}}$), a link budget of 80 dB is usually considered as sufficient to provide a robust communication link over a few meters. Therefore, the target output power of the transceiver is 0 dBm and the target sensitivity is -80 dBm.

Considering these performance requirements, the objectives with respect to the transceivers power consumption are defined. Currently, WBAN transceivers usually consume more than 10 mW and so dominate the available power budget. On the other hand, a power consumption on the order of 1 mW would be desirable, which is often referred to as the limit for autonomous operation in the literature, i.e., relying on energy harvesting only [115, 135, 143]. Given the fact, that the feasibility of sub-mW receiver frontends has been already demonstrated for proprietary 2.4 GHz transceivers [38], the target power consumption in RX-mode of the complete transceiver is set to about 1 mW. In TX-mode, the desired output power (0 dBm) sets the ultimate boundary of the power consumption. Considering that at least one-tenth of the dissipated power should be converted into RF output power delivered to the

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[1] 1P7M means 1 Poly layer and 7 Metal layers.

antenna, a power consumption clearly below 10 mW in TX-mode is set as the design goal. Another requirement with respect to the power supply is to operate from the typical deep submicron CMOS supply voltage of 1.0 V in order to facilitate the integration of a sensor interface together with the transceiver in the future.

Finally, a supplemental objective of this project is to analyze the possibilities of including RF energy harvesting with as little impact on the transceiver as possible. This means that neither the TX output power nor the RX sensitivity shall be affected significantly while using the same antenna as the transceiver in order to avoid additional external components.

This book is organized as follows:

1. Chapter 2 provides a background about recent low-power transceivers for WBAN applications by reviewing the state of the art. In particular, the recent publications are categorized in three groups, namely narrow-band TRXs such as this work that usually comply with a WBAN standard, wide-band TRXs employing a proprietary signaling, and for completeness pulsed ultra wide-band TRXs.
2. Chapter 3 presents the architectural consideration for the proposed transceiver. Four main strategies are identified which are essential to achieve an ultra-low power consumption. First of all, the selection of the overall RX architecture is discussed with its impact on the individual blocks, which eventually results in a zero-IF architecture for the proposed transceiver. Second, the number of active RF blocks has to be minimized in order to end up with as few RF nodes as possible that have to be driven by power-hungry circuits. Third, the remaining RF nodes have to be implemented with a high impedance level, because this leads to a low-required transconductance in the driving blocks and so reduces the power consumption. Finally, a low-complexity demodulation scheme avoiding quadrature multi-bit analog-to-digital converters (ADCs) is needed. Therefore, the proposed transceiver employs a phase-domain ADC (Ph-ADC) which needs only four bits of resolution to demodulate the incoming signal.
3. Chapter 4 describes the implementation of the transceiver at the circuit level. Being a key building block in any narrow-band receiver, this section begins with the design of the frequency synthesizer, in particular the evaluation of the topologies for quadrature generation with low-power consumption. Then, the selected topology, namely a quadrature voltage controlled oscillator (QVCO), is refined to improve the accuracy and to implement direct modulation. The second section describes the design of the RF frontend, where the main focus is to maximize the internal RF impedance using a transformer. In the third section, the base-band part of the receiver is detailed, whose key element is the demodulator using a 4-bit Ph-ADC. Finally, the performance of the transceiver as a whole is evaluated, also in conjunction with a commercially available BLE transceiver. In TX-mode a power consumption of 5.9 mW is measured for delivering an output power of 1.6 dBm to the antenna, which corresponds to a total efficiency of 24.5 %. In RX-mode, the transceiver consumes only 1.1 mW and achieves a sensitivity of −81.4 dBm using a passive RF front-end topology without LNA.

4. In Chap. 5 the possibilities for including an RF energy harvester with the previously presented TRX front-end are studied. A fundamental problem that has to be resolved is the decoupling of the harvester from the TRX while using the same antenna. In the proposed architecture, the harvester is decoupled from the TX with an RF-switch that can be turned on passively, i.e., the incoming RF power is converted by a start-up rectifier in order to activate the switch. To decouple the harvester from the RX, the non-linear impedances of the harvester and mixer are exploited. The proposed harvester also comprises a supply management circuit to charge an external energy storage device. The correct functionality of the harvester is verified experimentally using pulsed RF signals as emitted from wireless local area network (WLAN) routers showing that a large holding capacitance can be charged for a distances of up to about 30 cm. The measurements also verify that the harvester hardly affects the TRX performance, i.e., the degradation is less than 0.5 dB.
5. Finally, Chap. 6 presents the conclusions of this book, highlighting the most important contributions. Moreover, the measured performance of the presented transceiver is compared to the state-of-the-art based on different performance metrics. Also, an outlook to possible future work is given.